communications earth & environment

A Nature Portfolio journal

Article

https://doi.org/10.1038/s43247-025-02859-0

Strengthening pollutant control and resource recovery can enhance sustainable waste incineration in China

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Municipal solid waste incineration is increasingly used in China to balance urban growth with environmental and energy demands, yet challenges remain in pollutant control and by-product utilization. Here we compile operational data from 876 incineration plants across China and apply life cycle assessment models to systematically evaluate their environmental and economic performance. We find advanced flue gas treatment reduces harmful emissions but slightly compromises carbon benefits, whereas optimized leachate management achieves both emission reduction and carbon gains. Fly ash resource utilization can further improve environmental and economic outcomes, while waste classification and co-incineration strategies enhance plant viability. Our scenario simulations suggest that stricter emission standards, expanded classification, and targeted co-incineration can yield substantial carbon-negative and financial benefits. These findings highlight the synergistic potential of pollution control and resource utilization in shaping the sustainable transition of China's waste-to-energy industry.

China, one of the world's largest producers of municipal solid waste (MSW), processed 310 million tonnes of MSW in 2022, with incineration accounting for 75% of the total treatment due to its compact footprint and energy recovery potential[1,2]. The substantial volume and market scale have driven the rapid expansion of incineration infrastructure, now exceeding 2000 facilities with mechanical grate incinerators dominantly and circulating fluidized beds[3]. Mechanical grate incinerator dominates due to operational stability and low maintenance, with capacities ranging from 300 to 1000 tonnes/day[4]. In contrast, circulating fluidized bed incinerators offer higher combustion efficiency and fuel flexibility but require auxiliary fuels for sustained operation[5]. Notably, both technologies achieve thermal efficiencies exceeding 80%, highlighting the maturity of China's municipal solid waste incineration (MSWI) technology.

Nonetheless, environmental challenges associated with by-product management persist, constraining the industry's sustainable development. Incineration by-products—including leachate, flue gas, fly ash, and bottom slag—are linked to water and, air pollution as well as solid waste treatment issues[6]. Leachate, generated during MSW storage, can account for 10–40% of total MSW volume[7]. While membrane technology remains the dominant treatment method, it produces 15–25% of concentrate which is difficult to manage[8]. To address this, biochemical treatment and back-spray incinerator have been extensively studied and have been piloted at a limited number of incineration plants[9–11]. Flue gas purification represents an even greater concern, given the complex MSW composition and resulting pollutant diversity, including particulates, acid gases, toxic dioxins, and heavy metals[12]. Flue gas treatment technologies in China typically include SNCR/SCR denitrification, dry/semi-dry/wet desulfurization, activated carbon adsorption, and bag filters[13,14]. With rising demand for ultra-low emissions, integrated systems using multi-stage denitrification and deacidification have emerged, markedly improving synergistic pollution control. However, fly ash—classified as hazardous due to its heavy metals and dioxin content—remains a critical by-product[15]. While landfill-based stabilization is still common, resource utilization strategies such as cement kiln co-processing, molten rock wool production, and ceramsite sintering are increasingly adopted under China's "waste-free city" initiative[16,17]. Whether concerning incinerator type/scale or various gas–liquid–solid by-product treatment technologies, their environmental and economic impacts vary considerably. Therefore, a comprehensive assessment is required to compare these technologies and to identify more sustainable options adapted to regional contexts.

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Despite the advantages of MSWI in terms of efficient waste reduction and energy recovery, the high proportion of food waste in China's MSW poses many challenges for incineration plants, such as high leachate production and low combustion efficiency[18]. Therefore, optimizing front-end waste sorting, especially food waste separation, is vital to improving incineration performance. In recent years, China has gradually shifted from a traditional mixed waste treatment model to a refined waste separation system and has conducted environmental assessments on waste separation practices in several large cities[19]. For instance, in Shanghai, emissions from MSW treatment decreased by 54% following the implementation of waste segregation[20]. In Beijing, after food waste was separated from recyclables, incineration of only the remaining waste emerged as the optimal treatment model, reducing greenhouse gas emissions from MSW treatment by 72%[21]. These findings demonstrate that a comprehensive waste classification system not only enhances incineration efficiency but also reduces environmental pollution. However, many studies on waste classification often overlook its potential impact on the economics of incineration plants. While waste classification optimizes MSW composition and increases its calorific value, it also reduces the volume of MSW entering the incinerator, potentially impacting incineration plant operations. Actually, in cities where waste classification is not yet fully implemented, many incineration plants are already operating at low loads due to overcapacity, which has a remarkable impact on their operational benefits[22]. In response to this phenomenon, many incineration companies have adopted co-incineration strategies to expand the types of waste processed and enhance furnace utilization efficiency. Among them, co-incineration of municipal sludge, aged waste, and general industrial solid waste has emerged as a primary approach adopted by some incineration plants[23]. However, the composition and calorific value of aged waste and general industrial solid waste vary markedly across regions due to differences in economic development and climatic conditions, making it difficult to form a unified technology pattern for these two co-incineration strategies. In contrast, the calorific value of municipal sludge is relatively stable and requires urgent treatment that is costly individually[24]. Given these characteristics, sludge co-incineration warrants further research and evaluation from both incineration plant operation and sludge management perspectives. If proven environmentally and economically feasible, its technical model could be replicated nationwide, unlike the region-specific adaptations required for general industrial solid waste and aged waste. Whether it is the operational efficiency of incineration plants, their environmental impact, or the maximum sludge co-incineration capacity, all of these factors are fundamentally influenced by waste classification. Therefore, there is an urgent need to conduct comprehensive assessments of waste classification, incineration, and co-incineration across different regions to propose targeted improvement strategies.

Accurately assessing the environmental and economic performance of the MSWI industry across regions and proposing targeted sustainable waste management strategies requires representative high-resolution data. However, most studies often focus on direct emissions from individual facilities or city/provincial analyses using regional averages, overlooking the implications of heterogeneity in MSW composition, incineration technologies, and pollution control practices on the whole life cycle of MSWI in various regions. This results in data errors and limits policy relevance. For example, Han et al.[25] focused only on the carbon emissions from MSW treatment in Shanghai, and the optimization strategies they proposed have limited applicability at the national scale. Kang et al.[26] extended the analysis to the national level, but they relied on regional representative data to approximate city-level MSW treatment emission factors, which fails to capture inter-city heterogeneity. Similarly, Liu et al., Guo et al. and Xiao et al[27–29]. calculated province/city-level MSW treatment emissions by adopting uniform emission factors. By contrast, Liu et al. further considered variations in MSW composition and calorific value across cities and evaluated the carbon emissions and power generation performance of all MSWI facilities nationwide[30]. Nevertheless, this study did not account for the environmental impacts of diverse end-of-pipe treatment technologies. Furthermore, existing studies often focus on individual treatment processes within the MSWI industry under different system boundaries. For instance, Han et al.[3] analyzed the life-cycle impacts of different incinerator types and co-incineration scenarios, while Zhai et al.[31] assessed the carbon emissions associated with various fly ash treatment technologies. Han et al.[7] further compared multiple leachate treatment options. Although these studies provide valuable insights into the environmental performance of specific processes, their lack of an integrated perspective makes it difficult to capture the interactions among different subsystems and the overall environmental impacts of MSWI facilities. Building on the above research gaps and limitations, this study aims to address three key questions: (1) Within a unified system boundary, to what extent do different incinerator types/scales and gas–liquid–solid by-product treatment technologies affect the overall environmental and economic performance of the MSWI industry, and which technologies hold the potential for wider adoption across different regions in China? (2) Given the regional variations in MSW composition, calorific value, and incineration conditions, can waste classification and sludge co-incineration enhance the sustainability of MSWI? (3) Under current and future scenarios, to what extent can incineration plants deliver environmental and economic benefits across China's regions under the combined influence of technologies, strategies, and policies?

In this study, we employed a bottom-up approach to compile operational data from 876 incineration plants in 2022, covering MSW composition, calorific value, plant distribution and scale, actual loads, incinerator type, and detailed information on gas-liquid-solid pollutant treatment technologies. Using this database and a life cycle framework, we evaluated plant-level carbon emissions and economic performance, and further explored the optimization potential of the regional incineration industry under realistic conditions. Subsequently, drawing on historical MSW treatment data, we projected MSWI trends from 2022 to 2035. The carbon and economic co-benefits of the future MSWI sector—driven by MSW growth, waste classification promotion, region-specific co-incineration, pollution control upgrades, and by-product resource utilization—were estimated through scenario analysis. Building on these high-resolution and systematic analyses, we flexibly provide tailor-made recommendations for the future development of MSWI across different regions. These insights offer valuable reference for the transition from rapid MSW treatment to sustainable management—thereby supporting climate goals and economic gains.

Results

Spatial distribution and application technology status of China's waste incineration facilities

A comprehensive geographical database identified 876 MSWI plants in China, including 1948 incinerators (Detailed information is available in Supplementary data S1). Figure 1 presents an overview of their operational status at the end of 2022, detailing incinerator types, geographic distribution, operational scale, actual incineration volumes, and back-end treatment technologies. The geographical coordinates and operational specifications of each plant are provided in Supplementary Information A. These plants span 30 provinces, with a combined design capacity of 329 million tonnes/year. However, actual total incineration volumes account for only 73% of this capacity, indicating widespread underutilization. Notably, Guangdong, Zhejiang, Henan, Hebei, and Anhui each have design capacities exceeding 14.87 million tonnes/year—substantially above the national average (10.97 million tonnes/year)—yet their load rates are markedly lower. Among the 876 plants, 35 use only circulating fluidized bed incinerators, mainly in northern China. Mechanical grate incinerators are deployed in 826 plants (89.4%), with broad geographic coverage, particularly in coastal provinces. The remaining 11 plants employ a hybrid of mechanical grate and circulating fluidized bed technologies. Regarding unit scale, 79.8% of incinerators fall within the 300–700 tonnes/day range. In general, large-scale incinerators outperform small-scale incinerators in terms of energy efficiency[32]. Hence, there is considerable potential for GHG mitigation by integrating the operational scale of small-scale incinerators.

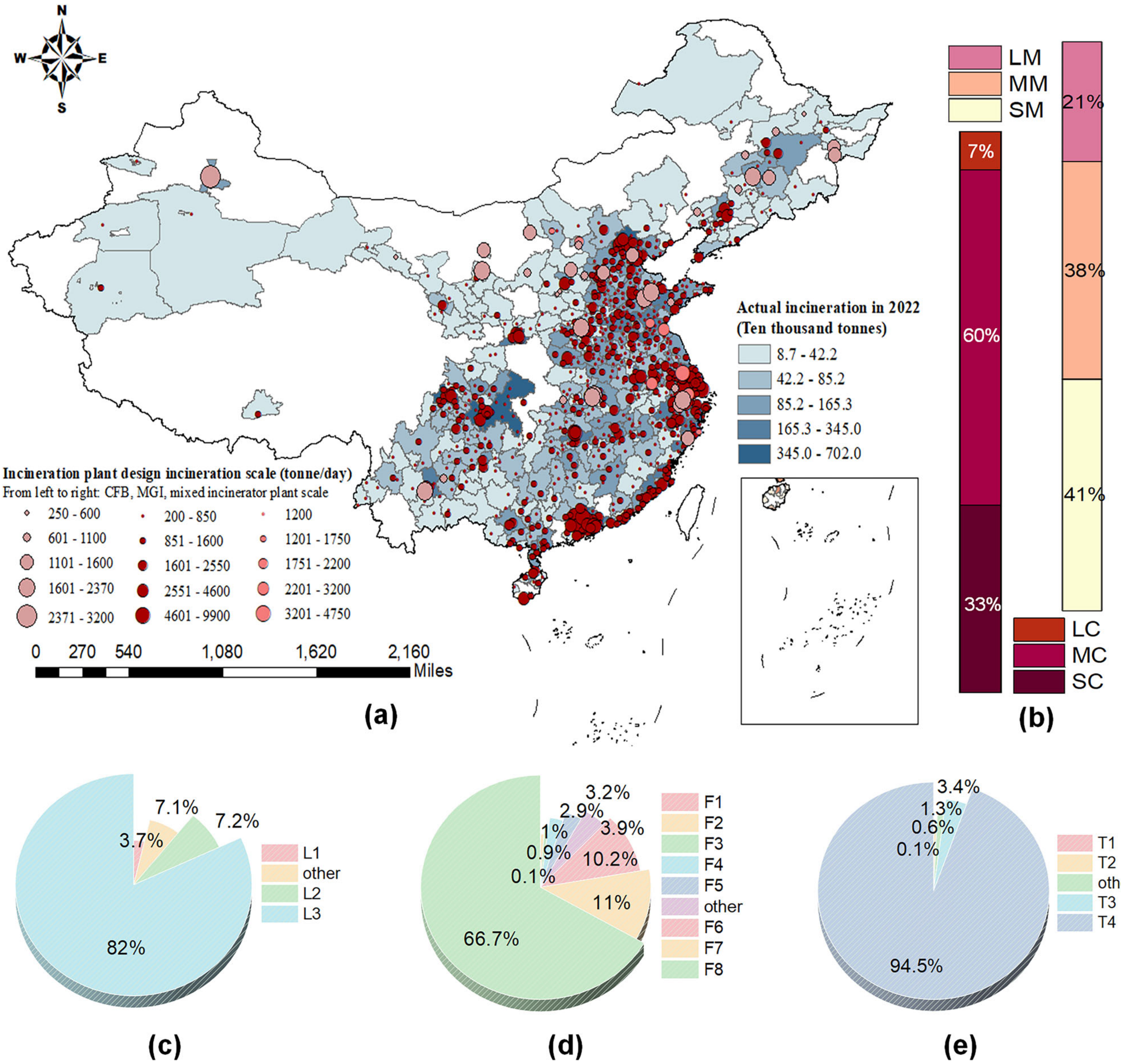
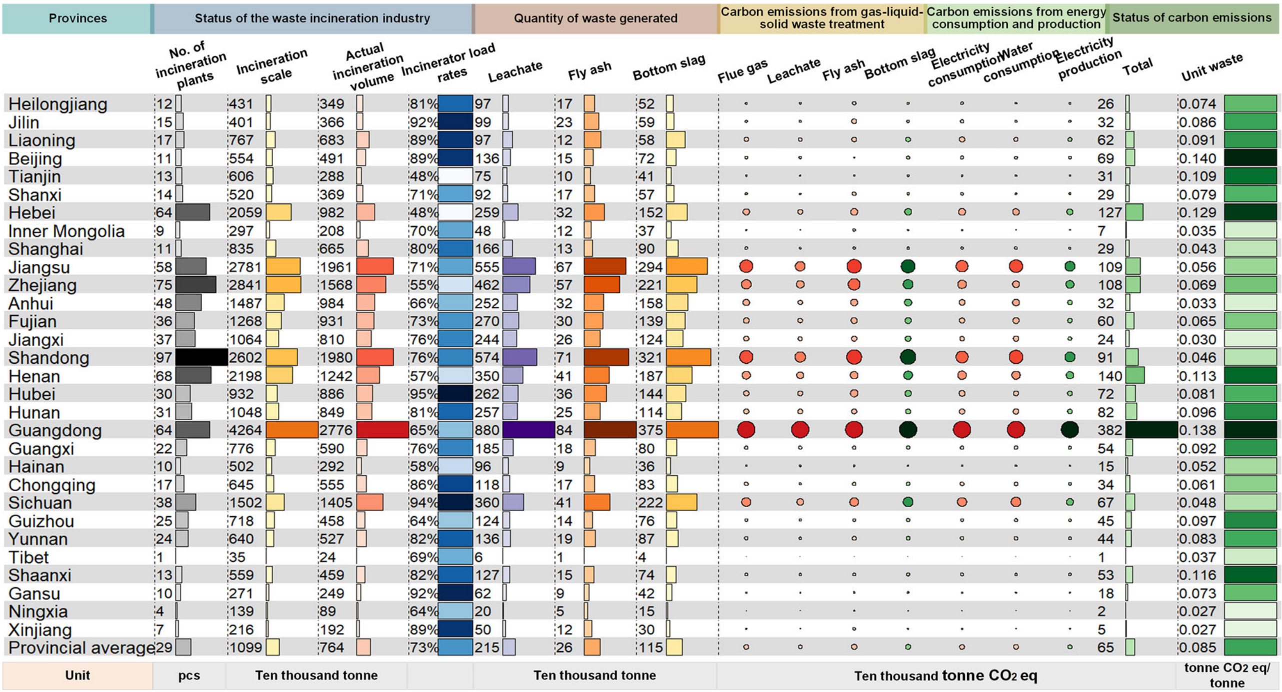


Fig. 1 | Spatial distribution and pollutant control technology status of Chinese waste incineration plants. a Spatial distribution of incineration plants of different scales nationwide. **b** Share of different incinerators nationwide. **c–e** Share of incineration plant gas, liquid and solid waste treatment technologies. SM/MM/LM—Small/ Medium/ Large scale mechanical grate incinerator, SC/MC/LC—Small/ Medium/Large scale circulating fluidized bed. L1 - UASB + Two-stage A/O + UF + STRO + STRO, L2 - Hydrolytic acidification + Two-stage A/O + UF + Fenton oxidation + Biological Aerated Filter, L3 - UASB + Two-stage A/O + UF + NF + RO. F1 - SNCR + SER + semi-dry + dry + activated carbon adsorption + bag filter, F2 - SNCR + SER + semi-dry + dry + activated carbon adsorption + bag filter, F3 - SNCR + semi-dry + dry + activated carbon adsorption + bag filter + SCR + wet, F4 - SNCR + PNCR + semi-dry + dry + activated carbon adsorption + bag filter, F5 - semi-dry + activated carbon adsorption + bag filter, F6 - SNCR + semi-dry+ dry + activated carbon adsorption + bag filter + SCR, F7 - SNCR + semi-dry + activated carbon adsorption + bag filter, F8 - SNCR + semi-dry + dry + activated carbon adsorption + bag filter. T1 - glassy slags through melting, T2 - sintering ceramsite, T3 - co-processing in cement kilns, T4 - solidification/stabilization landfilling.

MSWI plants generate several by-products during operation, including leachate, flue gas, and fly ash, all of which require stringent treatment to meet emission standards. In China, membrane-based treatment is the dominant approach for leachate management, with the UASB + MBR + NF + RO (L3) technology configuration accounting for 82% of applications. Other membrane technologies, such as UASB + MBR + STRO + STRO (L2) and IOC + MBR + TUF + RO (L1), also hold market shares of 7.2% and 3.7%, respectively. TUF membrane systems are primarily deployed in Shandong, Hunan, and Jiangxi, mostly within China's Everbright Environmental Enterprises. STRO membrane technology is mainly concentrated in Chongqing, followed by Anhui, Shandong, and Xinjiang.

For flue gas purification technology, 66.7% of the enterprises have adopted SNCR + semi-dry + dry + activated carbon adsorption + bag dust removal technology (F8). This is followed by SNCR + semi-dry + activated carbon adsorption + bag filter technology (F7) and SNCR + semi-dry + dry + activated carbon adsorption + bag filter + SCR technology (F6), which represent 11% and 10.2% of the total, respectively. The former is predominantly used in Chongqing, Guangdong, Shandong, and Heilongjiang, while the latter is common in Henan, Hebei, Jiangsu, Beijing, and Shaanxi. The other flue gas combination technologies have relatively small market shares, which are sporadically scattered throughout various provinces in China. For fly ash generated during flue gas purification, 94.5% of the plants selected solidification/stabilization to landfill (T4), largely due to its low



Provinces	No. of incineration plants	Incineration scale	Actual incineration volume	Incinerator load rates	Leachate	Fly ash	Bottom slag	Total	Unit waste
Heilongjiang	12	431	349	81%	97	17	52	26	0.074
Jilin	15	401	366	92%	99	23	59	32	0.086
Liaoning	17	767	683	89%	97	12	58	62	0.091
Beijing	11	554	491	89%	136	15	72	69	0.140
Tianjin	13	606	288	48%	75	10	41	31	0.109
Shanxi	14	520	369	71%	92	17	57	29	0.079
Hebei	64	2059	982	48%	259	32	152	127	0.129
Inner Mongolia	9	297	208	70%	48	12	37	7	0.035
Shanghai	11	835	665	80%	166	13	90	29	0.043
Jiangsu	58	2781	1961	71%	555	67	294	109	0.056
Zhejiang	75	2841	1568	55%	462	57	221	108	0.069
Anhui	48	1487	984	66%	252	32	158	32	0.033
Fujian	36	1268	931	73%	270	30	139	60	0.065
Jiangxi	37	1064	810	76%	244	26	124	24	0.030
Shandong	97	2602	1980	76%	574	71	321	91	0.046
Henan	68	2198	1242	57%	350	41	187	140	0.113
Hubei	30	932	886	95%	262	36	144	72	0.081
Hunan	31	1048	849	81%	257	25	114	82	0.096
Guangdong	64	4264	2776	65%	880	84	375	382	0.138
Guangxi	22	776	590	76%	185	18	80	54	0.092
Hainan	10	502	292	58%	96	9	36	15	0.052
Chongqing	17	645	555	86%	118	17	83	34	0.061
Sichuan	38	1502	1405	94%	360	41	222	67	0.048
Guizhou	25	718	458	64%	124	14	76	45	0.097
Yunnan	24	640	527	82%	136	19	87	44	0.083
Tibet	1	35	24	69%	6	1	4	1	0.037
Shaanxi	13	559	459	82%	127	15	74	53	0.116
Gansu	10	271	249	92%	62	9	42	18	0.073
Ningxia	4	139	89	64%	20	5	15	2	0.027
Xinjiang	7	216	192	89%	50	12	30	5	0.027
Provincial average	29	1099	764	73%	215	26	115	65	0.085
Unit	pcs	Ten thousand tonne	Ten thousand tonne		Ten thousand tonne	Ten thousand tonne	Ten thousand tonne	Ten thousand tonne CO2 eq	tonne CO2 eq/ tonne

Fig. 2 | Pollutant production and carbon emission status of provincial waste incineration industry in China. In provincial carbon accounting of by-product treatment, energy use and output, and total waste incineration, red and green denote positive values and negative values of carbon emissions, respectively. Wherein, positive values represent carbon burdens, while negative values represent carbon benefits.

capital and operational costs. Cement kiln co-processing is applied in only 3.4% of plants (T3), primarily in Beijing, Shandong, and Henan. Fly ash sintering to produce ceramsite (T2) is mainly practiced in Tianjin (0.6%), while glass slag production from fly ash (T1) is concentrated in Jiangsu (0.1%). Although several fly ash resource utilization technologies have been developed in China, large-scale adoption remains constrained by multiple factors. High capital investment costs and low-value-added product revenues have rendered many facilities financially unsustainable once government subsidies were withdrawn. In addition, construction materials derived from fly ash face limited market acceptance, and the deceleration of China's infrastructure construction sector has further depressed upstream production. Overall, technical, economic, and market constraints have slowed the expansion of fly ash resource recovery nationwide, and there is still a long way to go before achieving full resource utilization.

Regional distribution of carbon emissions from China's incineration industry

An in-depth analysis of back-end treatment and carbon emissions from MSW incineration was conducted across 30 Chinese provinces, based on operational data from MSW incineration plants in 2022 (Fig. 2 and Supplementary data S7). Results demonstrate that the 240 million tonnes of MSWI nationwide generated approximately 65.4 million tonnes of leachate, 7.9 million tonnes of fly ash, and 35.2 million tonnes of slag. The generation of these byproducts varies substantially across provinces, shaped by differences in incineration volume, incinerator type and scale, back-end treatment technologies, and regional climatic conditions. Among these, incineration volume is the dominant factor, as evidenced by the high outputs in Guangdong, Shandong, Jiangsu, Zhejiang, and Sichuan. Besides, under the influence of incineration volume, the ranking of leachate, fly ash, and bottom slag production remained basically the same in all provinces. Minor deviations in leachate and fly ash rankings are observed in a few provinces. Beyond incineration volume, leachate output is influenced by both climatic conditions and the progress of municipal waste classification. For example, in Heilongjiang, Shaanxi, Beijing, and particularly Hubei, underdeveloped classification systems have led to a high proportion of food waste, thereby increasing leachate generation. In contrast, although Guangxi and Hunan exhibit relatively low food waste content, their humid climates result in high moisture levels in MSW, which also contributes to elevated leachate production. Fujian and Hainan are simultaneously impacted by both humid climatic conditions and lagging classification efforts, resulting in consistently high levels of leachate output. For fly ash, the provinces with the largest ranking deviations are Inner Mongolia, Xinjiang, Jilin, Heilongjiang, and Shanxi. This is primarily due to the extensive deployment of circulating fluidized bed incinerators, which account for 54.2%, 48.9%, 47.1%, 35.2%, and 29.5% of the total incineration capacity, respectively.

From a life-cycle perspective, carbon emissions from MSWI primarily arise from electricity consumption, leachate treatment, flue gas purification, fly ash treatment, and electricity production by incinerator. Results indicate that, at the national level, MSWI has become a net carbon-negative activity, generating environmental benefits equivalent to 18.5 million tonnes CO_2 eq/year. Although the carbon reduction achieved by MSWI accounts for only about 0.16% of China's total CO_2 emissions in 2022 (11.48 billion tonnes), its significance should not be underestimated. With the full implementation of a national carbon market, these surplus negative-carbon credits could also support decarbonization goals in other industries. It should be noted that with the rapid expansion of renewable energy in China, the share of conventional coal-fired power in the electricity mix will gradually decline. This trend is expected to weaken the substitution effect of waste-to-energy generation, thereby reducing its net carbon-negative benefits. To offset this limitation, improving the power generation efficiency of MSWI plants should become a research priority in the future. Meanwhile, it is also necessary to progressively adopt low-carbon technologies in other treatment processes, such as flue gas carbon capture and utilization, to further consolidate the sector's mitigation potential. Among all provinces, Guangdong contributes nearly 21% of the national carbon-negative benefits, making it the largest contributor. However, when considering unit-level benefits, Beijing leads with 0.14 tonnes CO_2 eq avoided per tonne of MSW incinerated. This performance is attributed to the advanced technologies deployed in its facilities—particularly in the treatment and resource recovery of fly ash. These findings suggest that while expanding MSWI is essential to realizing net carbon-negative outcomes, optimizing its carbon efficiency is equally important. Breakdown by treatment segment reveals that flue gas is the largest source of positive carbon emissions, accounting for 63.7% of the total. Provinces such as Shanghai, Jiangsu, Zhejiang, Anhui, and Fujian exhibit proportions exceeding the national average. Electricity consumption in incineration plants is the second-largest contributor, responsible for 17.3% of emissions. Heilongjiang, Jilin, and Liaoning stand out, with contributions of 19.37%, 19.99%, and 19.68%, respectively. Beijing, Tianjin, Hebei, Shanxi, Shaanxi, Gansu, Ningxia, and Xinjiang follow closely, with shares ranging from 18% to 19%. Emissions from leachate and fly ash treatment contribute approximately 9% each—equivalent to 7.09 million and 7.4 million tonnes CO_2 eq/year, respectively. Notably, provinces such as Heilongjiang, Jilin, Shanxi, Inner Mongolia, Ningxia, and Xinjiang show fly ash emission shares exceeding 13%, well above the national average.

Economic operating benefits of China's waste incineration industry

Economic performance is a key determinant of the long-term sustainability of MSWI facilities. In 2022, the total annual economic revenue from MSWI nationwide reached RMB 7.05 billion. Guangdong, Shandong, Jiangsu, Zhejiang, and Sichuan are the top contributors, accounting for 16%, 9%, 9%, 8%, and 5% of the national total, respectively (Fig. 3 and Supplementary data S9). Henan, Hubei, Hebei, Fujian, Anhui, and Hunan formed the second tier, each contributing 3–5%, while the remaining provinces accounted for just 1–2% each. The provincial rankings of unit incineration benefits are similar to those of total economic benefits, with only a few provinces experiencing changes. Notably, Jilin, Tianjin, Sichuan, and Shanghai have the largest differences in these two rankings. The total economic benefits of incineration in Jilin and Tianjin represent only 1–2% of the national total, but their unit incineration benefits are much higher than the national average (RMB 27.6/tonne). In contrast, Sichuan and Shanghai have better total economic benefits (RMB 357 and 142 million) but poor unit economic benefits (RMB 25.4/tonne and RMB 21.4/tonne). This phenomenon indicates that provinces with high incineration volumes do not necessarily achieve favorable economic returns and that improving unit economic benefits should be the focus of the incineration industry. Based on this situation, a comprehensive review and analysis of the cost and revenue structure of incineration plants is essential.

The economic structure of the MSWI industry encompasses capital investment, management and maintenance costs, electricity and water expenses, treatment costs for leachate, flue gas, fly ash, and bottom slag, and revenue streams include MSW treatment fees and electricity generation. Among all expenditures, capital investment occupies the largest share, averaging 46% across provinces. Economically developed provinces such as Beijing, Shanghai, and Guangdong consistently report above-average capital costs. Most provinces incur management, maintenance, leachate treatment, fly ash treatment, and flue gas purification costs within the 7–11% range. However, several regions warrant specific attention. For example, Xinjiang reports disproportionately high shares of management and leachate treatment costs, while fly ash treatment accounts for 19% in Ningxia, 18% in Tibet, 15% in Inner Mongolia, and 14% in Jilin. For flue gas purification, Xinjiang, Inner Mongolia, Gansu, Shanxi, and Shaanxi rank among the top five provinces, markedly exceeding the national average. The high costs in specific treatment stages within these regions highlight the pressing need for technological improvement. Moreover, electricity costs also play a critical role in the operational profitability of MSWI plants and are closely related to the design scale of incinerators. Under equivalent MSW treatment loads, larger incinerators typically exhibit lower electricity consumption. Therefore, reducing the energy consumption of small-scale facilities should be a key focus of future research. In terms of economic revenues, electricity production, MSW disposal fees and slag disposal represent 40%, 37% and 23% of total revenues, respectively. Although electricity generation constitutes the largest share, current power generation efficiency remains suboptimal, indicating that there is still much improvement to be made. Meanwhile, as national subsidies for waste-to-energy gradually phase out, feed-in tariffs for MSWI are gradually converging to the traditional coal-fired tariff. In the future, regional electricity price differences will become an important factor affecting the level of incineration industry revenue. In a fully liberalized market, low electricity price regions—particularly small plants in central and western China—may encounter financial pressure. To mitigate this, we recommend establishing an MSWI feed-in tariff adjustment mechanism, such as setting an industry-specific minimum tariff or mandating a baseline purchase price, to protect its public service attributes and operational sustainability. Moreover, with the anticipated decline in electricity prices driven by the growth of renewable energy, ensuring the stable operation of incineration plants as critical environmental infrastructure will become increasingly challenging. We suggest drawing on power sector reform experience by introducing a dual-track tariff system combining capacity-based tariffs (providing stable compensation based on processing capacity) and market-based electricity pricing (incentivizing efficiency). This approach balances operational stability with economic performance. Although bottom slag currently contributes the least to revenue, the resource utilization of incineration by-products holds considerable economic potential. Achieving low-cost, high-value recovery from such by-products remains a key challenge for advancing solid waste management.

Carbon-negative potential of the waste incineration industry under the baseline scenario

The carbon-negative potential of existing MSWI plants was evaluated through the implementation of several strategies, including technology transfer, waste classification, co-incineration, and full-load operation. Among these, Full-load operation of incineration facilities emerged as the most effective, yielding an estimated 8.8 million tonnes of CO_2 eq in environmental benefits (Fig. 4 and Supplementary data S8). Guangdong, Hebei, and Henan demonstrate the greatest gains from this strategy due to their large design capacities and previously low utilization rates. From a practical perspective, economically developed provinces with high incineration capacities—such as Guangdong, Zhejiang, and Jiangsu—do not have enough fresh MSW to incinerate. If MSW generation in these regions continues to fall short of the designed treatment capacity in the near term, co-incineration with other waste materials such as sludge could be a viable option to improve capacity utilization. In contrast, many remote provinces—including Tibet, Inner Mongolia, Xinjiang, Shanxi, Heilongjiang, and Yunnan—still dispose of substantial amounts of MSW through landfilling. If these MSW originally destined for landfills could be transported to incineration plants, the facilities could operate at full capacity. Additionally, these provinces currently do not mandate fly ash resource recovery, so the excess landfill space could be used to process fly ash, to save operational costs. Once the economic benefits of the plants improve, technology upgrades can be implemented gradually. Therefore, for these remote provinces with general economic conditions, it is recommended that local governments establish relevant policies to intensify the promotion of MSWI.

Fly ash treatment technology transfer, leachate treatment upgrades, and sludge co-incineration follow closely, contributing 7.8, 6.4, and 6.1 million tonnes CO_2 eq nationwide in environmental benefits, respectively. Economically developed eastern provinces such as Guangdong, Shandong, and Jiangsu still show the highest mitigation potential. Guangdong ranks first in all three optimization pathways, achieving reductions of 0.9, 0.8, and 0.7 million tonnes CO_2 eq, respectively. Central provinces such as Henan, Anhui, and Hubei follow, while western and remote regions like Ningxia and Tibet show comparatively low mitigation outcomes. Regional differences in various strategies are mainly influenced by factors such as incineration volume, MSW composition, calorific value, and technology type. For example, fly ash treatment typically relies on cement solidification, which consumes large amounts of cement and has limited potential for material recovery. Consequently, its environmental burden throughout its life cycle is particularly high. In this context, utilizing fly ash to manufacture products such as ceramsite, cement, and rock wool to replace traditional building materials can yield substantial emission reduction potential. Provinces with high incineration capacities, such as Guangdong, Zhejiang, Jiangsu, and Sichuan, have, in recent years, introduced a series of incentive policies to advance fly ash treatment technologies. These include establishing

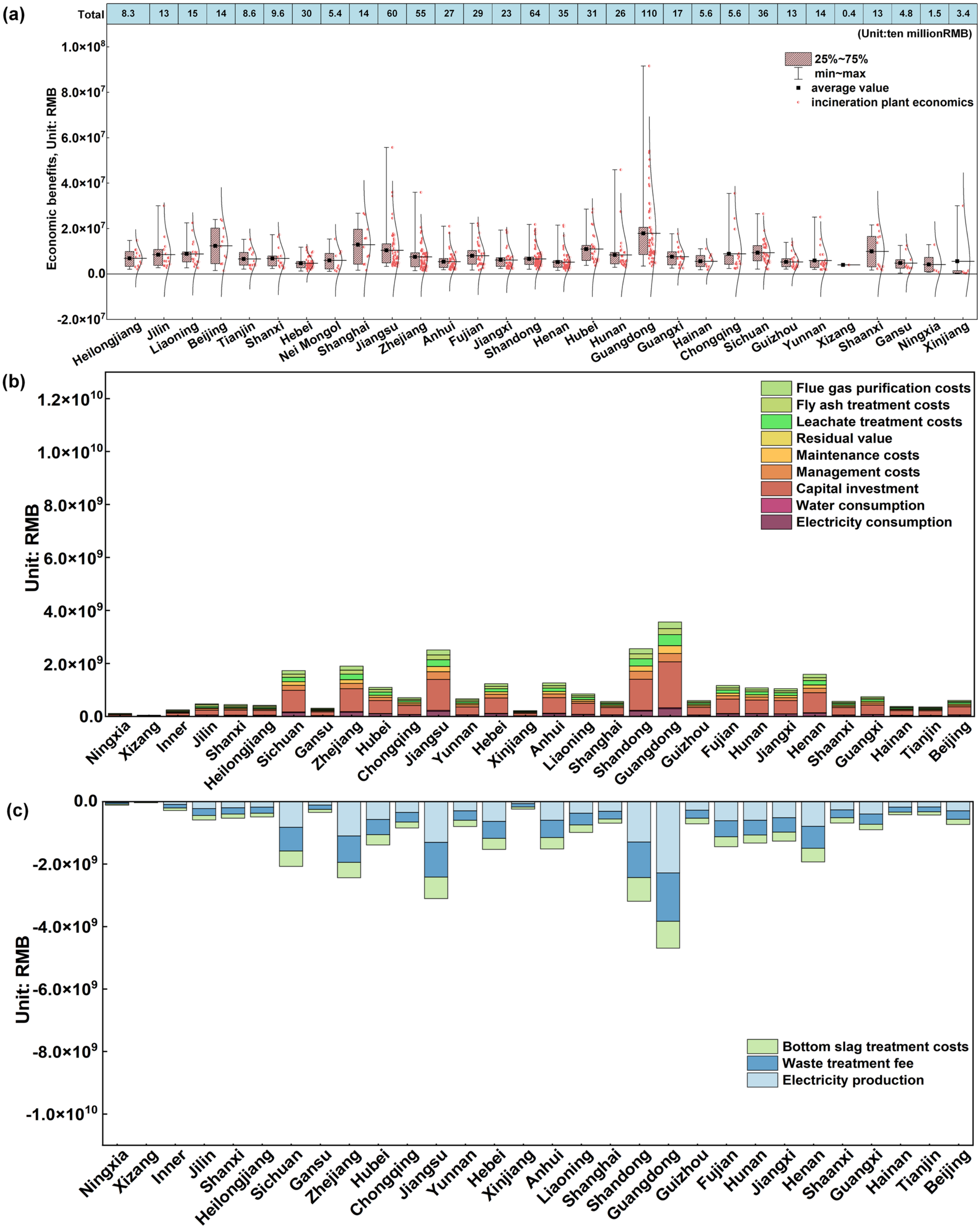


Fig. 3 | Economic performance of the provincial waste incineration industry in China. **a** Economic operation status of waste incineration plants by province. **b** Economic cost contribution analysis of the provincial waste incineration industry. **c** Economic revenue contribution analysis of the provincial waste incineration industry, including income from electricity sales, tipping fees for waste disposal, and resource recovery from bottom slag.

provincial-level remediation programs, reducing loan interest rates, and offering targeted subsidies to support industry development. For example, in Zhejiang Province, with joint financial support from both central and provincial governments, multiple fly ash resource utilization projects have entered the construction or trial operation stage. The province aims to reduce the landfill ratio of hazardous waste to below 5% by 2025. Therefore, for these provinces with adequate incentive mechanisms in place, the primary focus should now shift toward strengthening supervision and ensuring

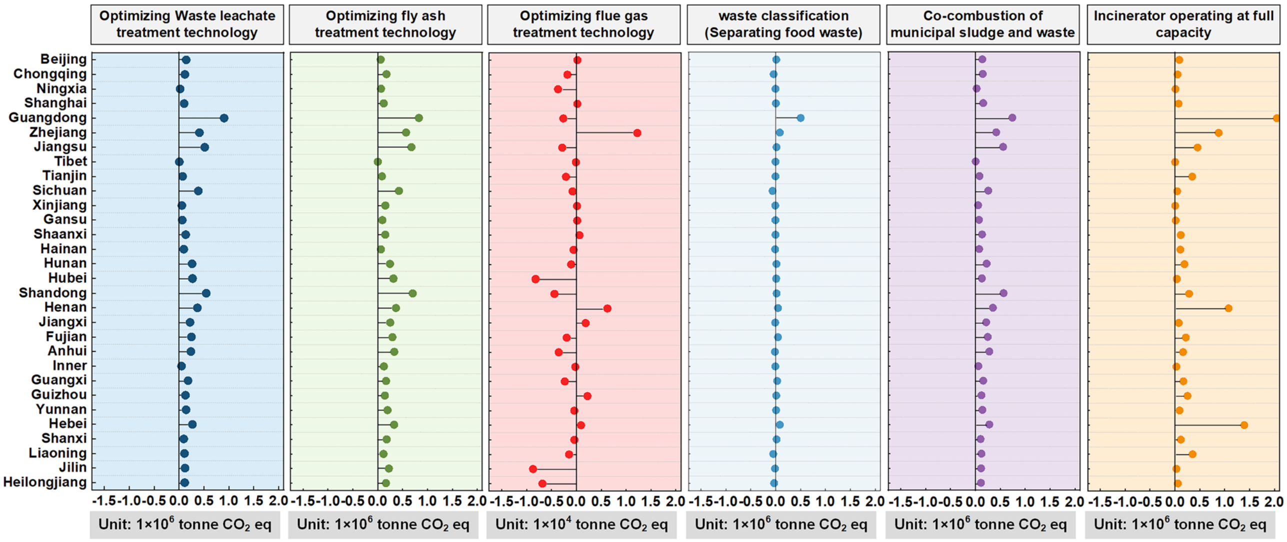


Fig. 4 | Carbon reduction potential under different optimization strategies in the provincial waste incineration industry.

regulatory compliance. In contrast, provinces such as Henan, Hubei, and Fujian—while also ranking among the major waste incinerating regions—have yet to implement equally strong measures, with policies largely remaining at the stage of advocating fly ash resource utilization. For these provinces, it is recommended that local governments expedite the introduction of region-specific policies and regulatory frameworks tailored to their economic and industrial contexts. As an initial step, pilot projects could be launched in several major cities within each province, with priority access to provincial environmental protection funds and simplified approval procedures during the trial period. Moreover, collaboration with well-established enterprises from regions such as Jiangsu and Zhejiang should be encouraged to leverage their operational experience, thereby enabling the rapid yet steady advancement of fly ash resource utilization.

The emission reduction effect of leachate is primarily driven by regional production volumes. Apart from incineration volumes, high food waste content and humid climate are important factors for increased production, so regions with these conditions should prioritize relevant technology upgrades. While in-furnace spraying combined with biochemical treatment can maximize environmental benefits, its application is largely limited to central and southern provinces. In northeastern regions, where winter temperatures are low, leachate is prone to freezing, markedly increasing pre-treatment costs. Moreover, in northern provinces, the low moisture content of waste during winter often results in higher COD and ammonia nitrogen concentrations, along with elevated inorganic salt levels. Direct furnace injection under these conditions may lead to slagging, corrosion, or even exceedances of dioxin emission limits. Therefore, for northern provinces, exploring more advanced membrane combination treatment + biochemical treatment pathways is a more practical approach. Promoting waste classification nationwide could generate 1.3 million tonnes of CO_2 eq environmental benefits. Classification reduces the quantity of MSW entering incinerators, but increases the calorific value of the residual waste and reduces leachate production. This resulted in positive carbon-negative gains in most provinces, with Guangdong, Zhejiang, and Hebei in the top three. The effectiveness of sludge co-incineration is positively correlated with total incineration volume and facility underutilization. In contrast, flue gas purification technology transfer slightly reduces overall carbon-negative benefits in most provinces, contributing only 0.22–0.34% of the gains realized by other strategies. However, it delivers notable reductions in other pollutants, such as nitrogen oxides and sulfur compounds (Details are provided in Supplementary Tables 17 and 18). Given that the MSWI sector is already carbon-negative and that flue gas control targets extend beyond carbon reduction, the moderate sacrifice of carbon benefits in exchange for multi-pollutant abatement is both reasonable and necessary. Currently, economically developed regions such as Jiangsu, Zhejiang, and Shanghai have implemented ultra-low emission standards stricter than those in the EU Industrial Emissions Directive, signaling a nationwide tightening of environmental regulations. In the subsequent implementation process, a phased approach could be adopted, starting with the Yangtze River Delta region, followed by key urban agglomerations, and then gradually extending to central and western regions. Additionally, considering regional disparities in economic capacity, regulatory frameworks should balance “rigid constraints” with “flexible space.” For example, the strictest limits can be applied directly to new facilities, while existing plants are granted a 3–5 year transition period. Smaller incinerators (e.g., county-level facilities) can be subject to moderately relaxed requirements, supported by subsidies for technical retrofits.

Future pathways toward more carbon-negative and cost-effective for the waste incineration industry

Across over 10000 projected scenarios, the negative-carbon benefits of MSWI by 2035 exhibit considerable regional variation but show a consistent trend of improvement nationwide (Fig. 5 and Supplementary data S12). Under the business-as-usual scenario, China’s MSWI sector is expected to deliver 32.83 million tonnes of CO_2 equivalent in negative emissions by 2035—an increase of 89% compared to 2022. Guangdong, Henan, Hunan, Liaoning, and Hebei are projected to experience the largest absolute gains, each exceeding 1 million tonnes of CO_2 eq. In contrast, Inner Mongolia, Liaoning, Xinjiang, Tibet, and Shanxi are expected to see the highest relative increases, each surpassing 200%. With the implementation of waste classification policies, although the volume of MSW sent to incineration plants has markedly decreased, incineration volumes in 2035 are still maintaining growth compared to 2022. Besides, waste classification has contributed to a notable increase in the calorific value of MSW and a substantial reduction in leachate production. The consolidated results suggest that the waste classification policy will not compromise the operation of incineration plants. Instead, it will further enhance their carbon-negative outcomes. By 2035, the MSWI sector is expected to achieve 92.5 million tonnes of CO_2 equivalent in carbon-negative benefits—a 407% increase from 2022. However, due to regional variations in incineration volumes, MSWI composition, calorific values, and leachate generation, the impact of waste separation differs across provinces. Henan, Hunan, Hebei, Shandong, and Liaoning rank highest in both total carbon-negative benefits and absolute growth following classification. Meanwhile, Hebei, Shaanxi, Henan, Guizhou, and Shanxi exhibit the most pronounced improvements in unit carbon benefits, with increases of 0.587, 0.539, 0.454, 0.368, and 0.314 tonnes CO_2 eq per tonne of MSW, respectively. To test the robustness of the findings, we conducted a sensitivity

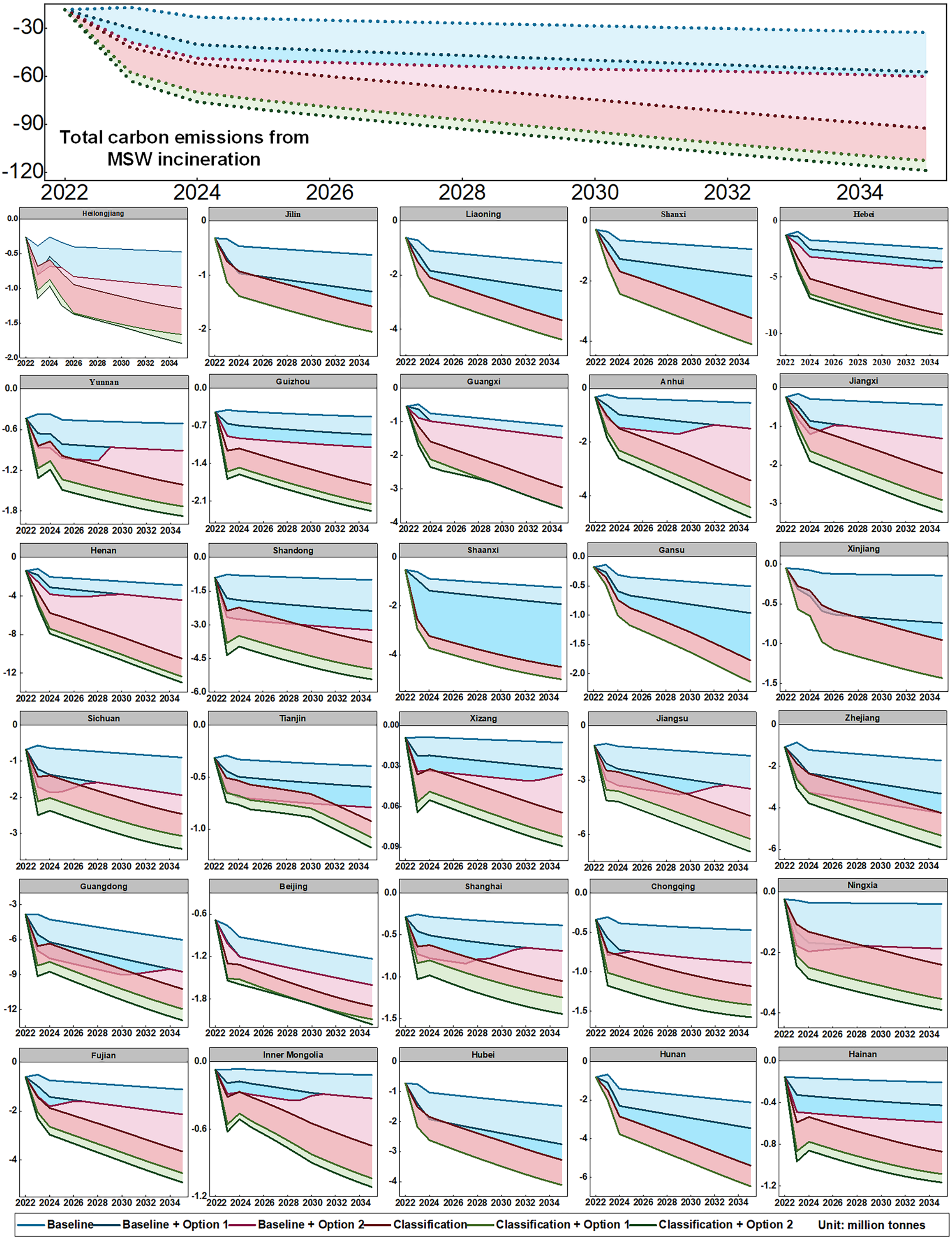


Fig. 5 | Carbon reduction potential of national/provincial waste incineration industry for 2022–2035. Baseline: From 2022 to 2035, MSWI follows the projected growth trend based on the forecast model, with no improvement strategies implemented. Option 1: Technology transfer for leachate treatment, flue gas purification, and fly ash treatment in incineration plants, prioritizing the selection of technologies with the best environmental and economic performance. Option 2: Based on technology transfer, adopt a sludge co-incineration strategy for plants operating below full capacity, maximizing incineration capacity utilization.

analysis assuming a 30% lag in classification speed. The results indicate that although the magnitude of carbon-negative benefits declines, the MSWI continues to deliver net carbon reductions across all provinces. High-incineration provinces such as Henan, Hebei, Guangdong, Shaanxi, and Jiangsu are the most sensitive, showing the largest absolute changes (detailed data are provided in Supplementary Table 11). Additionally, the sensitivity rankings of Shandong, Yunnan, Chongqing, and Hainan slightly improved compared to their original carbon emissions rankings under the classification process, which is related to the composition of food waste. If optimal strategies are fully implemented under the waste classification policy, the carbon-negative benefits of the incineration sector could rise by a further 145% by 2035, reaching 118.9 million tonnes CO_2 eq. Among the contributing measures, fly ash treatment technology transfer plays a dominant role, accounting for 48.9% of the total gain, followed by leachate technology transfer (27.3%) and sludge co-incineration (24%). To maximize these benefits, fly ash and leachate technologies should first be prioritized in high-incineration provinces such as Guangdong, Zhejiang, and Jiangsu. Co-incineration strategies should be targeted based on incinerator underutilization and regional incineration volumes to effectively assess and prioritize emission reduction potential. Given that the volume of sludge incinerated varies with the annual MSWI volume, only 21 provinces are positioned to participate in co-incineration scenarios from 2022 to 2035. Among these, Guangdong, Henan, Jiangsu, Zhejiang, and Shandong rank in the top five for total co-incineration benefits, representing 54% of the total, which deserves special attention. Although flue gas technology transfer slightly offsets carbon benefits, its impact is minimal, accounting for just 0.2% of total reductions. Therefore, incineration plants are encouraged to upgrade flue gas treatment systems to reduce emissions of other pollutants, such as NO_x and SO_2, with negligible compromise to their carbon mitigation performance.

Economically, the optimal scenario enables the MSWI sector to achieve RMB 364.3 billion in total benefits by 2035, representing a 169% increase over the baseline scenario (Fig. 6 and Supplementary data S13). While economic gains vary considerably across provinces (ranging from RMB 220 million to 33.8 billion), their growth patterns closely parallel those of carbon benefits. Provinces with high incineration volumes continue to dominate economic gains—Guangdong, Zhejiang, Hebei, Henan, and Jiangsu, all processing over 10 million tonnes of MSW annually, report cumulative increases of RMB 33.8, 31.9, 22.3, 20.5, and 18.4 billion, respectively. Chongqing, Sichuan, and Shandong remain among the top ten in economic growth despite experiencing negative growth rates in MSWI. This trend is closely linked to increases in MSW calorific value and advancements in pollutant control technologies. At the bottom of the list are remote provinces such as Xinjiang, Ningxia and Tibet. Despite regional disparities, waste classification consistently generates positive environmental and economic outcomes for incineration facilities. In 2035, under the optimal scenario, the calorific value of MSW improves across all provinces, raising the average share of electricity revenues from 40% to 49% (Supplementary Fig. 1). In 10 provinces—including Zhejiang, Jiangxi, and Gansu—electricity revenue shares increase by more than 10%. On the cost side, leachate treatment expenses drop markedly, with the national average falling from 10% to 1% due to the combined effects of classification and technological upgrades. 11 provinces, including Beijing, Tianjin, and Hebei, even achieve zero leachate treatment costs. Fly ash treatment costs decline from 9% to 5% of total expenditures, while flue gas purification costs increase slightly, from 8% to 10%. Overall, if incineration plants further reduce or recycle their by-products, the sector could unlock substantial economic gains, reinforcing the dual environmental and financial value of sustainable MSW management strategies. Further discussion is available in the Supplementary Discussion of Supplementary Information A.

Methods

Geospatial and operational database of 876 waste incineration plants in China

To obtain detailed information on the emission activities of China's MSWI sector, we established a national inventory covering operating data of 876 MSWI plants across the country during the period of 2002-2022. The dataset includes information on the MSWI plants' geographic distribution, treatment capacity, incinerator type, and back-end by-products (leachate, flue gas, fly ash, and bottom slag) treatment processes, as well as information on the actual MSW incineration volume, MSW composition, MSW calorific value, and sludge production in each province (see the Supplementary Note 1 and 2 for detailed data). Operational information—such as treatment capacity, incinerator type, operational years, and actual address—was sourced from the Open Platform for Automated Monitoring Data of Domestic Waste Incineration Power Plants (https://ljgk.envsc.cn/). Each plant was geolocated and cross-verified using Google Maps and the Skywatch platform (https://www.tianyancha.com). Given variations in MSW composition, calorific value, and by-product treatment technologies among plants, we collected approximately 600 corporate environmental impact assessment reports, over 100 official statements from China's Ministry of the Ecology and Environment, and more than 50 media reports. For the remaining over 100 plants with missing data (mainly concerning leachate, flue gas, and fly ash treatment), we inferred the distribution of treatment technologies using available plant data. Weighted average environmental and economic impacts were then calculated based on technology shares and applied to plants lacking this information. The actual MSWI volume for each province is sourced from the Statistical Yearbook of the Ministry of Housing and Urban-Rural Development of China (https://www.mohurd.gov.cn/), while sludge production data is obtained from the official websites of provincial ecological environment bureaus, water bureaus, and related agencies.

Carbon emission and economic benefits assessment of municipal solid waste incineration plants

Carbon emissions from MSWI plants are evaluated using LCA, distinguishing between direct and indirect sources[33,34]. Direct emissions refer to greenhouse gases released directly from the combustion of MSW and fossil fuels[35,36]. Indirect emissions include upstream greenhouse gas emissions associated with energy and chemical production[37]. Direct emissions are calculated following the Guidelines for the Preparation of Provincial Greenhouse Gas Inventories, while upstream emission factors for indirect emissions are sourced from China's local life-cycle calculation software (https://www.efootprint.net) — the efootprint platform (detailed LCA modeling is described in Supplementary Note 5.). The calculation process is shown in Eqs. (1)–(4):

$$E_{total} = (E_{CO_2,d,w} + E_{CO_2,d,f} + E_{CO_2,i,j}) \times TWI \tag{1}$$

where $E_{CO_2,d,w}$ - Direct carbon emissions from waste incineration; $E_{CO_2,d,f}$ - Direct carbon emissions from fossil fuel incineration; $E_{CO_2,i,j}$ - Indirect carbon emissions from chemicals, water and energy; TWI - Total waste incineration:

$$E_{CO_2,d,w} = CCW \times PMC_w \times CE \times \frac{44}{12} \tag{2}$$

where CCW - Carbon content in one tonne of waste, i.e. 20 %; PMC_w—Percentage of mineral carbon content, i.e. 39 %; CE—Waste incinerator combustion efficiency, i.e. 95 %; d—direct emission; w—municipal solid waste:

$$E_{CO_2,d,w} = CCW \times PMC_w \times CE \times \frac{44}{12} \tag{3}$$

where FFW - Fossil fuels required for incinerating one tonne of waste; PMC_f - Percentage of mineral carbon content, i.e. 80 %; CE - Waste incinerator combustion efficiency, i.e. 95 %:

$$E_{CO_2,i,j} = ADW_j \times EF_j \tag{4}$$

where ADW - Activity data consumption for incinerating one tonne of waste i.e., chemicals, energy and water; EF—Emission factor for relevant activity data.

Fig. 6 | Economic growth potential of the provincial waste incineration industry for 2022–2035. Situation 1 represents normal growth of waste incineration over time with no optimization strategies. Situation 2 represents normal growth with the adoption of best available strategies in all aspects.

MSW needs to undergo multiple processing stages from initial waste classification to final harmless discharge at the incineration plant. The detailed process flow is illustrated in Fig. 7. Herein, we have divided this process into seven parts in the life cycle analysis, i.e., water consumption of the incinerator, electricity consumption of the incinerator, leachate treatment, flue gas purification, fly ash treatment, slag treatment, and electricity output. In calculating the MSW incinerators, we found that the predominant types of incinerators used in MSWI plants nationwide are mechanical grate incinerators and circulating fluidized bed incinerators. Therefore, this study primarily focuses on these two types, categorizing the incinerators as small, medium, and large scale (detailed information is provided in the Supplementary Note 2). Additionally, leachate treatment encompasses five leachate treatment technologies and three leachate concentrate treatment methods, while flue gas purification involves eight treatment techniques. Fly ash can be treated through four resource recovery options, in addition to landfill, whereas slag treatment includes only one type of resource recovery method (detailed technology introduction is provided in the Supplementary Note 2). Regional differences in MSW calorific value can result in varying electricity outputs during the incineration process. Therefore, we collected the average MSW calorific value for each province (detailed data is provided in the Supplementary Note 1). The data collection process involved plant surveys, environmental impact assessment reports, and existing research literature. Additionally, since life cycle emission factors for electricity can vary by region, we have accounted for these regional differences when assessing the environmental impacts of electricity in MSWI plants across provinces.

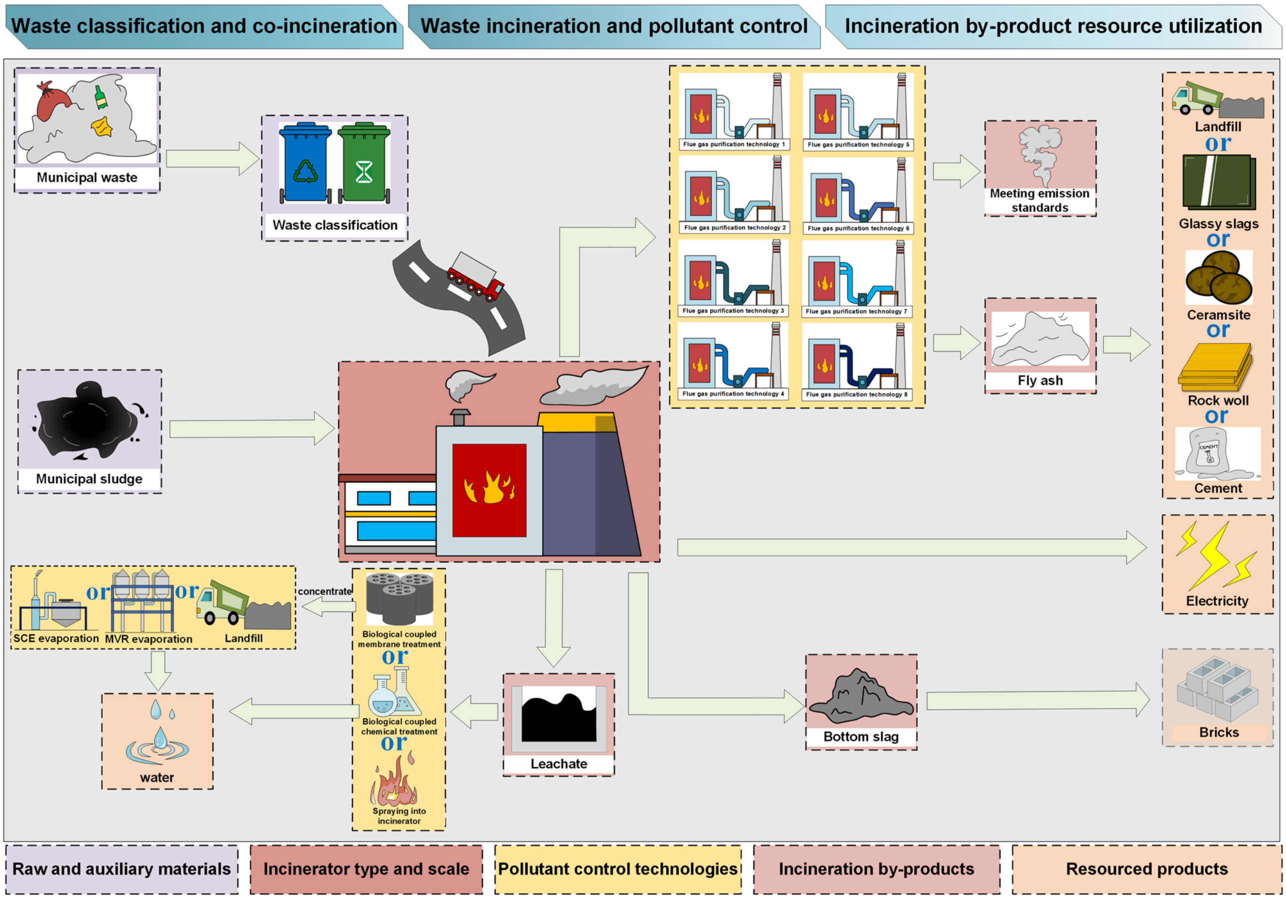


Fig. 7 | System boundary from waste classification to complete treatment of incineration by-products.

Economically, this study employs a dynamic life cycle costing model to provide a realistic assessment of MSWI plants, incorporating the time value of money for precise evaluation[38–40]. This approach integrates economic factors across the entire life cycle, encompassing capital costs, incinerator water and electricity consumption, leachate treatment, flue gas purification, fly ash disposal, management, maintenance, salvage value, and revenue. Revenue sources include bottom slag utilization, MSW treatment fees, and power generation income. Economic data for MSWI plants are sourced from enterprise environmental impact assessment reports. Raw material prices, obtained from enterprises or public sources, reflect average market values (China Price Information Network). Given regional variations in electricity prices due to differing power mixes, we assumed the thermal power feed-in price for each province as the waste-to-energy feed-in price. Based on the economic modeling framework applied by Liu et al. in the field of MSWI, which has been widely adopted in MSWI techno-economic analyses in China, we set the annual maintenance cost at 0.8% and the residual value at 10% of the initial investment[24]. The discount rate was set at 6%, consistent with both Liu et al. and commonly used values in waste-to-energy project evaluations[41–43]. Management costs, i.e. labor compensation, are based on the average salary of recent graduates[44]. All detailed economic data are provided in Supplementary Note 5. The mathematical model for cost estimation based on the evaluation index system is shown in Eqs. (5)–(7):

$$\begin{aligned} Dynamic\ LCC = C_0 - \sum_{t=0}^{T} I_i \times PV_{sum} + \sum_{t=0}^{T} O_i \times PV_{sum} \\ + \sum_{t=0}^{T} M_i \times PV_{sum} + \sum_{t=0}^{T} R_i \times PV_{sum} - S \times PV \end{aligned} \tag{5}$$

$$PV_{sum} = \frac{(1+r)^t - 1}{r \times (1+r)^t} \tag{6}$$

$$PV = \frac{1}{(1+r)^t} \tag{7}$$

where

C_0—capital cost; I—operational income (bottom slag utilization, waste treatment fees, and power generation income); O—operating cost (incinerator water and power consumption, leachate treatment, flue gas purification, and fly ash treatment); M—maintenance cost (the maintenance cost required for each technical equipment); R—management cost (the management cost required during each technical operation); T—life cycle; S — salvage value; i—various influencing factors (different revenue, technology operating cost, maintenance cost, and management cost); PVsum—present value sum; PV—discount factor; r—discount rate. These equations have been validated in previous MSWI techno-economic analyses and shown to produce consistent and reliable results[7,24,43].

Regional environmental and economic evaluation of waste incineration industry

By integrating plant-level datasets with life cycle calculations, we quantify both carbon emissions and economic performance across the MSW incineration industry in each Chinese province. The regional environmental and economic analysis is divided into three parts: assessing the current state of China's MSWI industry (with a baseline of 2022), exploring present optimization potential within the industry, and forecasting its future performance and optimization possibilities. The assessment of improvement potential in the MSWI sector includes technology upgrading/transfer (for leachate, flue gas, and fly ash treatment), waste classification, sludge co-incineration, and full-load operation of incinerators. To project MSW generation at the provincial level, we collected data on total MSW treatment, incineration, landfill, and other treatment volumes from 2002 to 2022 in the Statistical Yearbook of the Ministry of Housing and Urban-Rural Development of China (other treatment defaults to food waste treatment). Using these historical data, we applied models such as Holt's damped trend, polynomial regression, and linear regression to extend the MSW generation trend to 2035 with reference to past studies. Building on this, a waste classification step-by-step progression scenario is designed in this study, wherein provincial MSW composition is assumed to remain unchanged from 2022 to 2035. Based on actual situation and existing studies, each province was divided into three regions—unclassified, developing, and developed—each with distinct food waste separation rates. The proportion of the three zones will change over time, i.e., the unclassified and developing zones will gradually become developed zones. Detailed forecast modeling and classification information is provided in the Supplementary Note 3 and 4. Moreover, incineration plant pollutant control technologies improvements and sludge co-incineration are also incorporated in future projection scenarios, resulting in a total of more than 10,000 scenarios. In these optimization strategies, both LCA and LCC indicators were comprehensively considered, and technologies that demonstrated superior performance in terms of environmental benefits and economic outcomes were prioritized for implementation across incineration plants. The descriptions of different pollutant control technologies and their corresponding LCA and LCC results are provided in Supplementary Notes 2 and 5. Detailed description of the co-incineration strategy is given in Supplementary Note 6.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The datasets supporting the findings of this study, including the source data for all figures and tables, are provided as Supplementary Data and are also publicly available in Figshare[45] (https://doi.org/10.6084/m9.figshare.30119083).

Received: 2 June 2025; Accepted: 30 September 2025;

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Acknowledgements

The authors acknowledge financial support from the National Natural Science Foundation of China (52270135).

Author contributions

Q. H. contributed to conceptualization, methodology, data curation, and writing of the original draft. H. L. contributed to conceptualization and methodology. Y. G., J. T., Y. S., and G. W. contributed to writing, review and editing. Y. Z. contributed to investigation and data curation. G. C. contributed to writing, review and editing. All authors contributed to data interpretation, manuscript revision, and approved the final version of the paper.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-025-02859-0.

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Peer review information *Communications Earth and Environment* thanks Malak Anshassi, Huimin Liu and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Primary Handling Editors: Ta Yeong Wu, Somaparna Ghosh A peer review file is available.